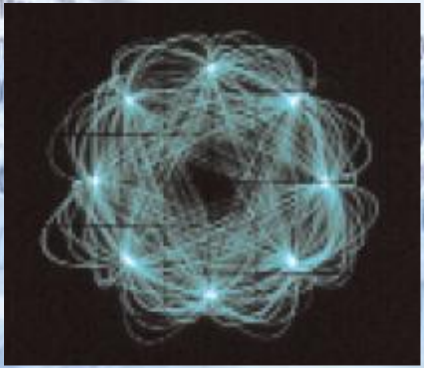
APCO Project 25 and Other Digital Radio Technologies Overview

NXDN™



DMR
DIGITAL MOBILE RADIO ASSOCIATION

DIGITAL WIRELESS · SANS FIL NUMÉRIQUE · INALÁMBRICO DIGITAL
P25

TETRA

Andy Ruschak
KK7TR

Origins of P25

FCC Federal Communications Commission

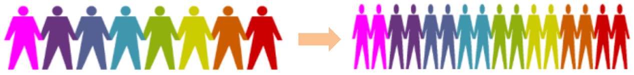
How did we get here? - Transition to Narrowband

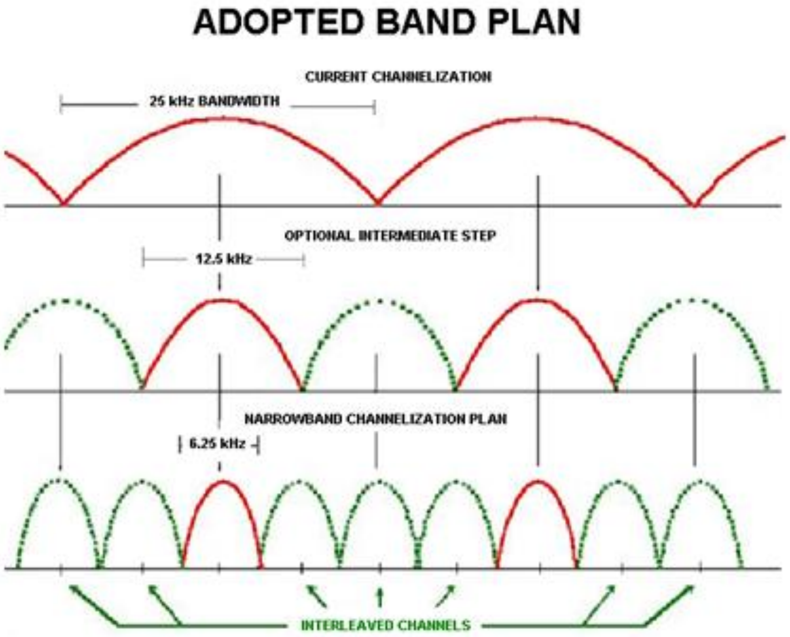
- 1980's – FCC, user representative organizations (APCO) and manufacturers looked for solutions to *spectrum overcrowding*
- Moving to narrower channel bandwidths selected as solution
- FCC ***requires*** migration from 25 KHz to 12.5 KHz by Jan 1, 2013
- FCC *expects* a transition to 6.25 KHz "e" using FDMA or 2/4-slot TDMA)

In case you don't think your amateur spectrum is valuable…

H.R. 607 (d) RECOVERED PUBLIC SAFETY SPECTRUM AUCTION.—Not later than 10 years after the date of enactment of this Act, the paired electromagnetic spectrum bands of **420–440** MHz and 450–470 MHz recovered as a result of the report and order required under subsection (c) shall be auctioned off by the Federal Communications Commission through a system of competitive bidding meeting the requirements of section 309 of the Communications Act of 1934.

Better Spectral efficiency = More Users





Why go Digital ?

- Manufacturers and user representative organizations realized that *analog narrowband operation imposes performance limitations* and isn't practical with very narrowband channels
- Digital operation offers considerable operational benefits to users – examples include additional voice capacity and easily added data applications
- There was no digital standard in place when the rules were formed
- P25 was an attempt to prevent a proprietary standards digital radio "Tower of Babel"

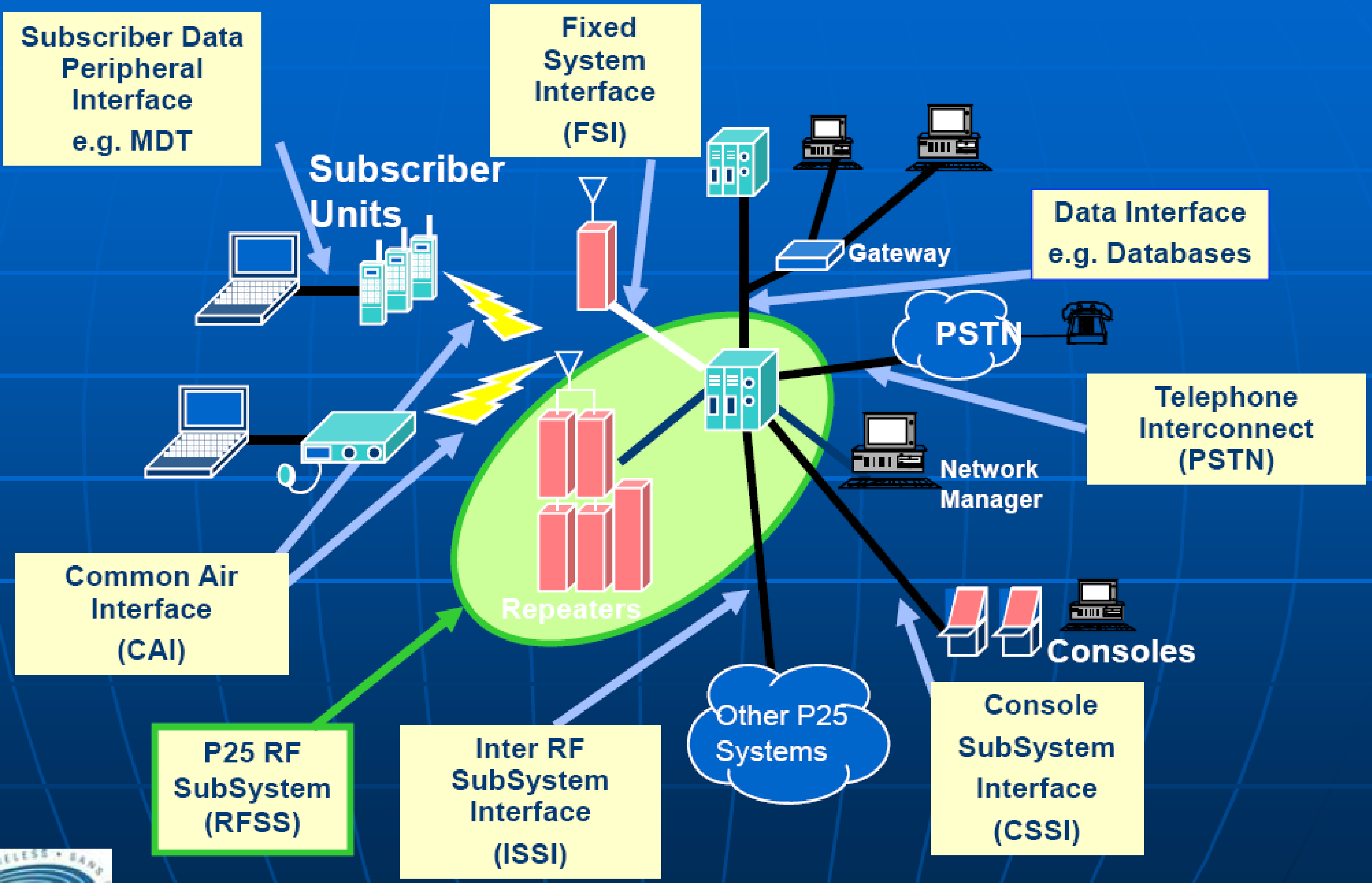
- Digital modulation in LMR has been around since the 1980's.
- User needs, technology and industry needed to converge, not diverge

What is Project 25 ?

- Standards developed by TIA/EIA-supported committee of manufacturers, system operators, and industry associations, guided by a *steering committee* of public safety and federal government radio system users. APCO = Association of Public Safety Communications Officials
- *Open* (public domain) standard for production and implementation of digital land mobile radio system infrastructure and subscriber equipment
- Defines a digital radio system technology that supports a wide range of advanced radio system features.
- *APCO is NOT a government agency and has no regulatory authority over any user - either public safety or private.*
  - For the first time in many years, a level playing field was created in the industry through the open standards process. Lessons learned from 9/11 and the DoD made it clear that interoperability must have priority.

TIA EIA APCO NASTD

Project 25 System Interfaces



Subscriber Data Peripheral Interface
e.g. MDT

Fixed System Interface
(FSI)

Data Interface
e.g. Databases

Telephone Interconnect
(PSTN)

Common Air Interface
(CAI)

P25 RF SubSystem
(RFSS)

Inter RF SubSystem Interface
(ISSI)

Console SubSystem Interface
(CSSI)

Is P25 Here to stay … yes ! Really…?

- Functional Capabilities and Benefits
- Grant and Funding Source Requirement - PSIC
- Federal & State Purchasing Requirements – DHS, RCW 43.105.330
- Interoperability - CAI and Intersystem Interfaces

Who manufactures P25 equipment?

- More than 12 manufacturers and growing

Who is using P25 ?

- > 1 million P25 subscriber radios deployed nationwide
- > 35 states have deployed, or deploying, statewide networks
- P.S., Federal & State Agencies, DoD, and more

DANIELS ELECTRONICS LTD.
DATRON
EFJohnson TECHNOLOGIES
HARRIS
Hytera
ICOM
KENWOOD
MIDLAND
RELM WIRELESS
TAIT radio communications
THALES
Vertex Standard
TECHNISONIC

P25 CAI (Common Air Interface)

- Consists of Modulation, Channel-Coding, and Vocoder standard
- Allows multi-vendor equipment to operate together with equivalent functionality in a basic communications mode
- Defines conventional and trunked infrastructure access algorithms, replacing vendor-specific (*proprietary*) access methods
- Does not specify TX power, RX sensitivity, or other technical specifications; these are manufacturer and market-driven capabilities where other TIA, IEEE, or FCC standards may apply

P25 Data Stream

4400 bps	Voice
2800 bps	FEC
2400 bps	C &S Data

9600 bps @ 12.5 kHz CH. BW

D-Star™ DV Data Stream

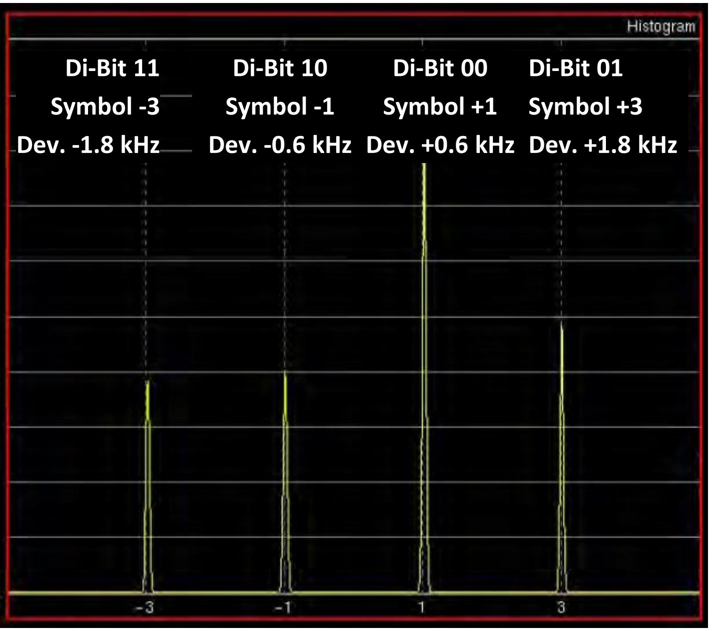
2400 bps	Voice
1200 bps	FEC
1200 bps	C &S Data

4800 bps @ 6.25 kHz CH. BW

C4FM Digital Modulation

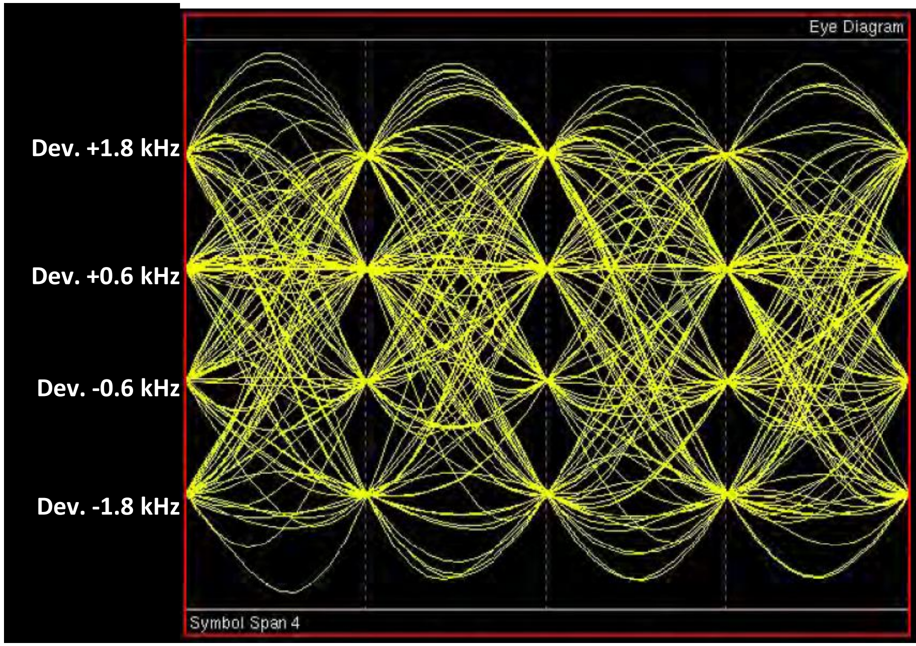
- C4FM – Constant Envelope 4-carrier (level) FSK modulation, 12.5 kHz, 9600 bps
- FSK to 4 deviation points around a center frequency
- Each state represent a binary number (DiBit/Symbol - 2 bits of information).
- Each carrier has a fixed offset and *never returns to the center frequency* - each transition is encoded to start from its last position
- FCC Emission designator 8K10F1E

Histogram (% symbols decoded over time)

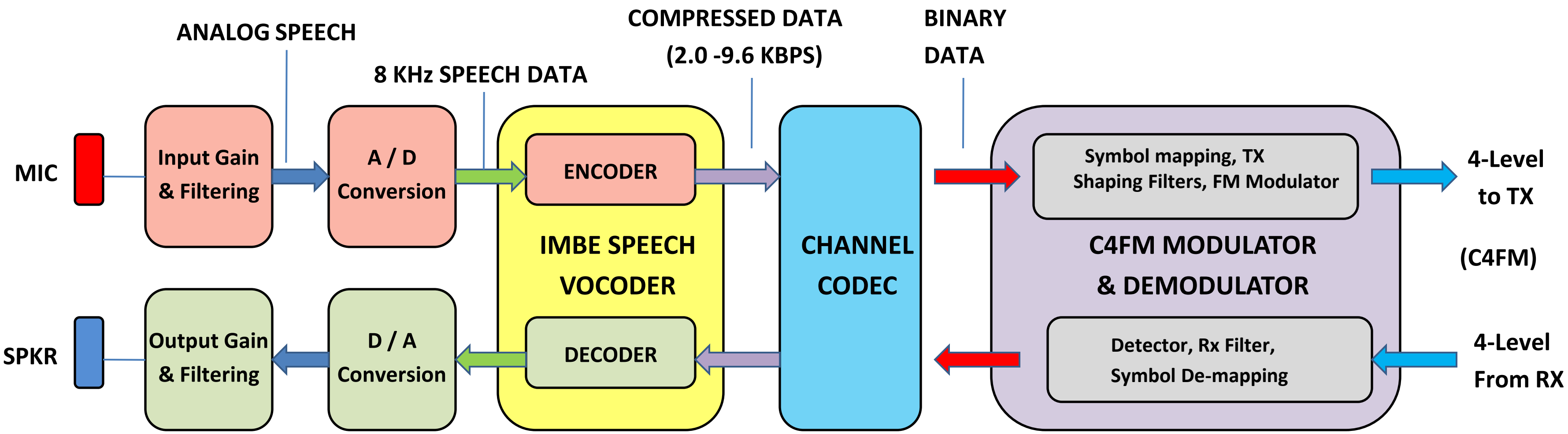


Plots of C4FM

'EYE" diagram (volts vs. time)



P25 Transceiver Diagram



ANALOG SPEECH

8 KHz SPEECH DATA

COMPRESSED DATA
(2.0 -9.6 KBPS)

BINARY
DATA

MIC

Input Gain
& Filtering

A / D
Conversion

ENCODER

IMBE SPEECH
VOCODER

DECODER

CHANNEL
CODEC

Symbol mapping, TX
Shaping Filters, FM Modulator

C4FM MODULATOR
& DEMODULATOR

Detector, Rx Filter,
Symbol De-mapping

4-Level
to TX

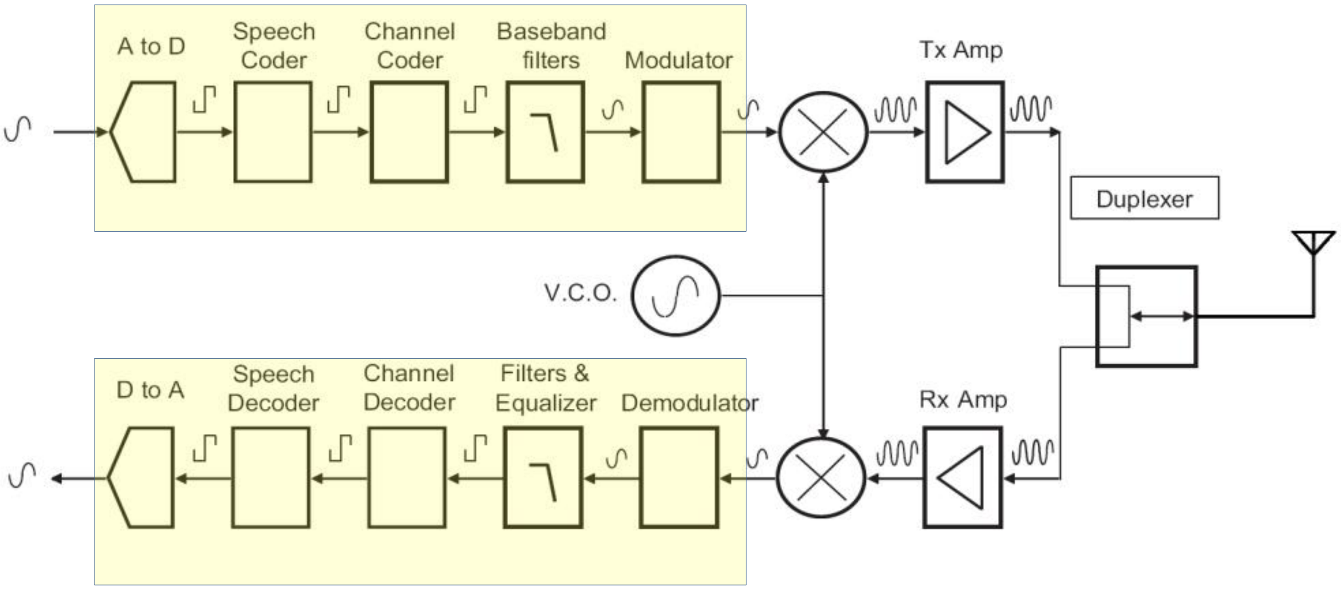
(C4FM)

4-Level
From RX

SPKR

Output Gain
& Filtering

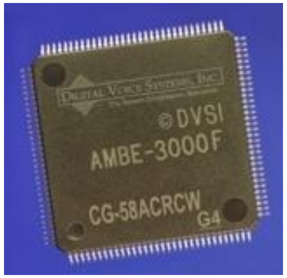
D / A
Conversion



VOCODING

Background

- Two Families: *Waveform* coders and *Model-Based* (Synthetic) coders
- *Model-based* speech coder - provides a *synthetic equivalent* of human
- Models audio segments as frequency-dependent *combination* of either *voiced* or *unvoiced* speech.
- *Perceptual* quality rather than waveform accuracy
- Significant research, testing and evaluation before selection by TIA
- Multiple vocoders in MOS tests, best voice quality in occupied bandwidth
- IMBE™ vocoder selected from Digital Voice Systems, Inc. (DVSI)
- Market barrier/cost of entry (licensing for IMBE™/AMBE™)



VOCODER tailored for human glottal tract audio patterns

- Models not optimized for pure note, DTMF, paging tones, etc.

DIGITAL VOICE SYSTEMS, INC.
The Speech Compression Specialists

VOCODING Processing Schemes

VOCODER performs error estimation during decoding - estimates the number of errors in each received frame. If the error estimate is below some threshold, it decodes the frame normally. If the error estimate is above the threshold, it may:

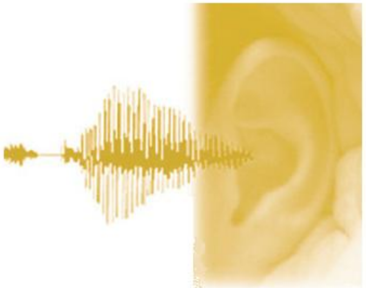
- *Repeat the frame* (low BER) - better to “stretch” the speech fragment than deliver a problem frame. Frame is 20 ms long, so a single repeat may not be noticeable to the human ear.

- *Performs adaptive smoothing of the frame* (intermediate BER) - takes info from previous frame and the next frame (two-frame look-ahead) to “smooth” effects of errored frame.

- *Mute the frame* (severe BER) - a replica of white noise is created, sometimes called “comfort noise.”

Human Signal Processing

- compensates for lost syllabic content



IMBE™ vs. AMBE™

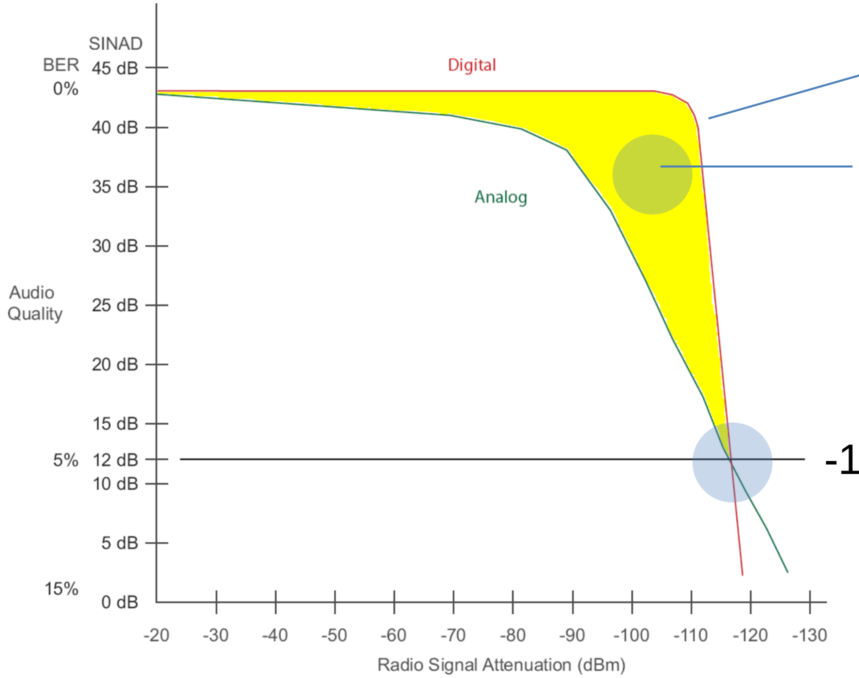
- IMBE™ implemented in all 1st generation P25 products since 1993
- 2006 – 2008 performance issues in LE and FD noise environments*
- Results of significant testing inconclusive – can't blame VOCODER 100%
- Pre-VOCODER noise reduction algorithms solve much of audio problem
- Improvements in radio ergonomic design and better training of personnel
- 2005 - P25 Committee adopted the Enhanced Full-Rate AMBE+2 Vocoder.
- V1.4 (2005) - improved audio quality and better tones reproduction, V1.6 (2009) offers improved noise suppression for fire service

*chain saw, wind, air mask low air alarm, siren, etc.

P25 Channel CODEC

Purpose

- Provides Error Correction and Data Protection
- Counteract effects of noise, fading and interference
- Error Correction Techniques include
  - Interleaving & Linear block (Hamming, Golay, Reed-Soloman) codes
  - Primitive BCH (Bose & Ray-Chaudhuri) and shortened cyclic codes



The "digital cliff"

Performance recovered through Error Correction

-119 dBm @ 5% BER

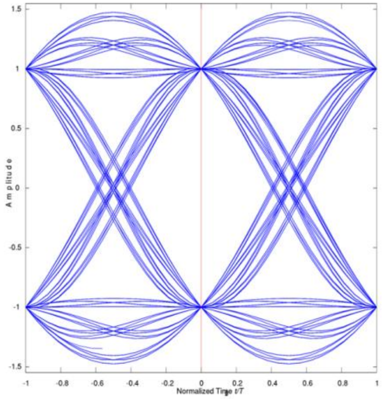
P25 Performance Characteristics

Digital vs. Analog

- Increased effects of multipath distortion
- Differing system performance at the edge of coverage area
  - *Sudden* vs. *Gradual* loss of intelligibility at fringe "digital cliff"
- Some reduction in S/N ratio due to narrower BW (12.5 kHz)
- Error correction offsets some of this
- Improved usability in fringe areas not possible with analog

Digital Radio Specific Phenomena

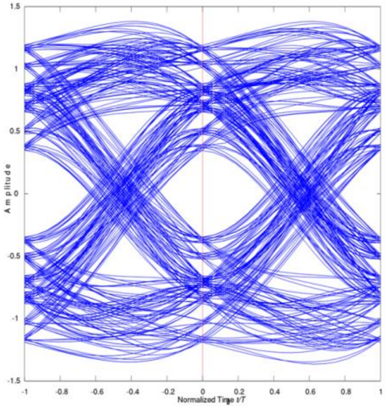
- BER > 5% - limit of EC and recoverable data /understandable speech
- ISI (Inter-Symbol Interference) issue addressed by advanced modulation



Ideal

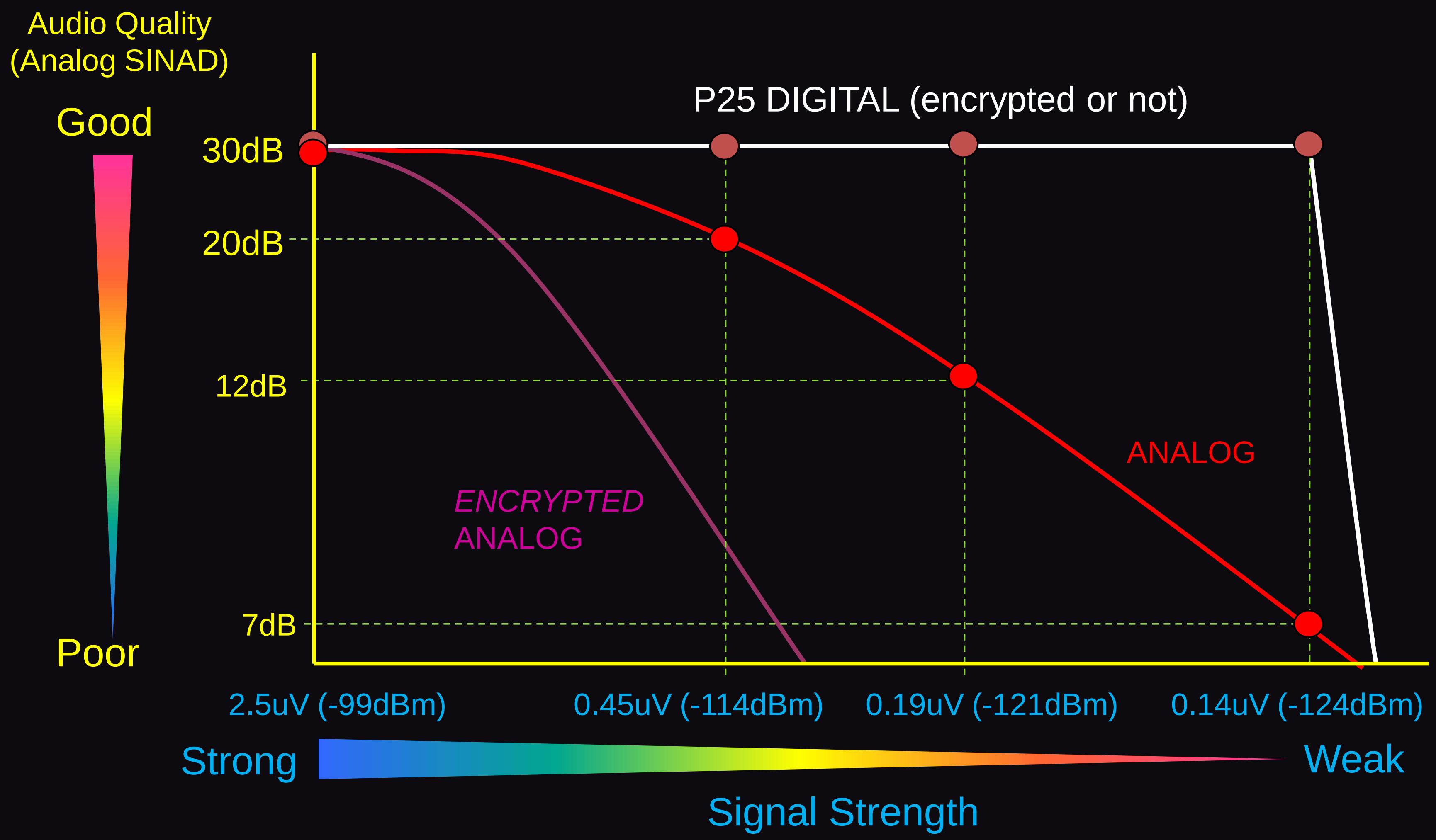
C4FM Eye Diagram

Phase Distortion



(multi-path)

Analog vs. Digital (P25 C4FM)
Simulated Coverage Comparison



Audio samples courtesy of Tait Communications

P25 Integrated Voice & Data Modes

- 2400 bps for (overhead) signaling and control functions
  ex. SELCAL, TG ID, network (repeater) access codes (NAC)
- Low Speed Data performance subject to packet size
- Supports confirmed or unconfirmed packet delivery
- Intended for custom user applications
  - -GPS AVL ('APRS' style)
  - - SMS text messaging
  - - Status & Telemetry
- Manufacturers offering API's for development
- Optimized for Digital Voice not Digital Data – a compromise

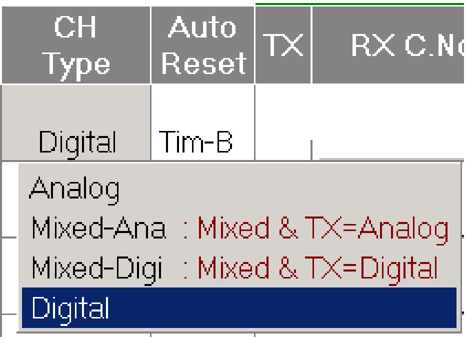
P25 Data Stream

4400 bps	Voice	
2800 bps	FEC	
2400 bps	C &S Data	← **IV&D**

P25 Mixed Mode Operation

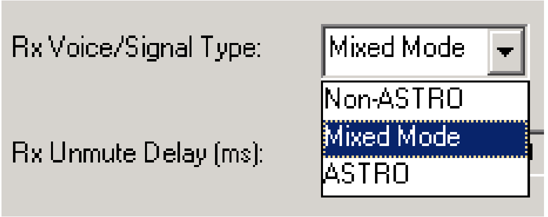
Auto-Detect and Switching between analog & digital modulation

- 48-bit (5 ms) sequence for frame sync sent at start of all transmissions
- Frame sync presence = digital mode, no frame sync = analog mode
- Base station switches operational mode accordingly
- Frame sync re-inserted every 180 msec. during TX for RX detection (late entry) and maintain digital operation
- Great for shared repeater use, migration and interoperability
- Mixed mode operation is a simple user programming setting



CH Type	Auto Reset	TX	RX C.N
Digital	Tim-B		

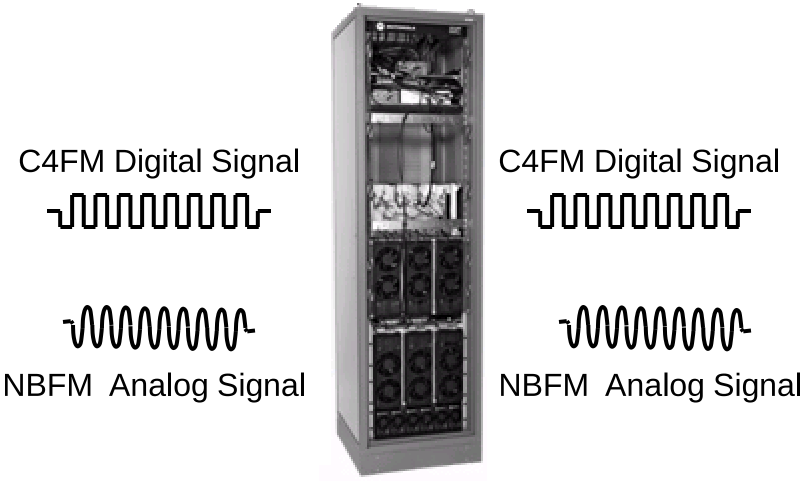
Analog
Mixed-Ana : Mixed & TX=Analog
Mixed-Digi : Mixed & TX=Digital
Digital



Rx Voice/Signal Type: Mixed Mode

Non-ASTRO
Mixed Mode
ASTRO

Rx Unmute Delay (ms):



P25 Phase II

Next Generation Technology Evolution – what is it and why ?

- Optimized for trunking – better ***capacity*** & control
- FCC mandated spectral efficiency
- One voice path @ 6.25 kHz, Data/Control Channel 4800 bps @ 6.25 kHz
- 6.25 kHz capability encouraged on all bands, *required* on 700 MHz in 2017

Phase 2 Technical Characteristics

- 12 kbps air link rate, 2 slot TDMA channel access, Half-Rate Vocoder (3600 bps)
- Two modulation schemes, PM for uplink, CQPSK for downlink
- Bi-directional signaling (dynamic power control, adj. site info)

Goals

- Improved VOCODER efficiency and voice quality
- Backward compatibility with C4FM Phase 1 units

User and Industry Impact

- New radio certification VHF/UHF in 2011, 700 MHz in 2015
- Transition VHF/UHF/800 – no req.   700 MHz in 2017

@ 6.25 kHz BW now!

P25 Phase 2 Technology

Asymmetric Uplink & Downlink – *specifically trunked operation*

Mobiles & Portables

- H-CPM transmit (Harmonized Continuous Phase Modulation)
  - Constant envelope for easier PA design (Class C amp) same as used in P25 Phase 1 design, economy
  - Allows coherent (FM) receiver in the base station for good sensitivity

Base Stations

- H-CQPSK transmit (Harmonized Continuous Quadrature PSK)
  - Linear 4-level for non-coherent (AM) subscriber receiver
  - Excellent simulcast delay spread

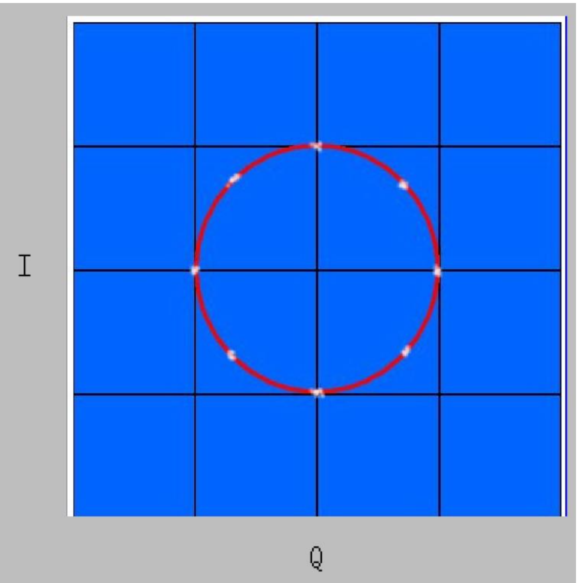
Why do this modulation combination?… follow the money !

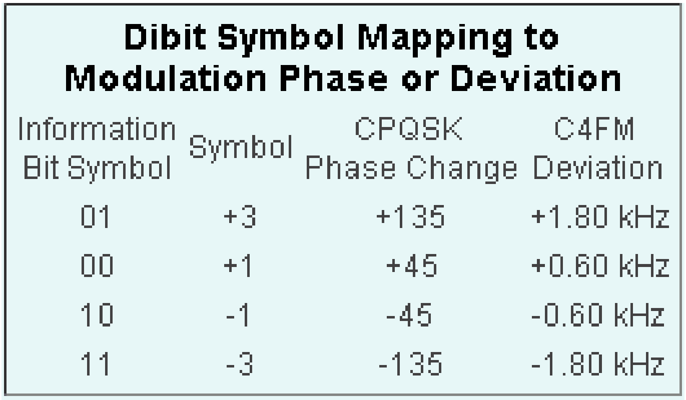
1. **Radio Subscriber Unit Cost**
   - Manufacturers are cheap. Customers are cheaper (but not as cheap as hams ☺)
   - Leverage existing investment in Class C amps, RX front-ends, 8-hour battery life
2. **CQPSK is a robust modulation protocol**, good for reliable data signaling
   - Simulcast transmission is widely used in trunk system, offers increased site spacing. Due to tolerance to time delay of arrival and phase distortion. Greater site spacing = less required sites = cheaper

C4FM vs. CQPSK – *compatibility magic*

- C4FM is a *constant amplitude* modulation, the I/Q modulation plot is a circle, with the 4 decision points referenced by the phase offset/shift from zero due to a carrier frequency shift.
- CQPSK requires a phase shift to depict a symbol and imparts an amplitude (AM) component to the signal
- Data rate, BW and bits per symbol identical between the two modulations
- Key to compatibility with CQPSK modulation is the symbols or decision points *"appear" in the same position* in the I/Q plane regardless of modulation formats

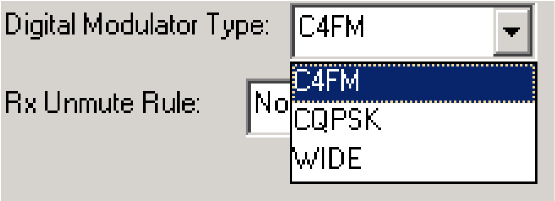
C4FM I-Q Map





Dibit Symbol Mapping to Modulation Phase or Deviation

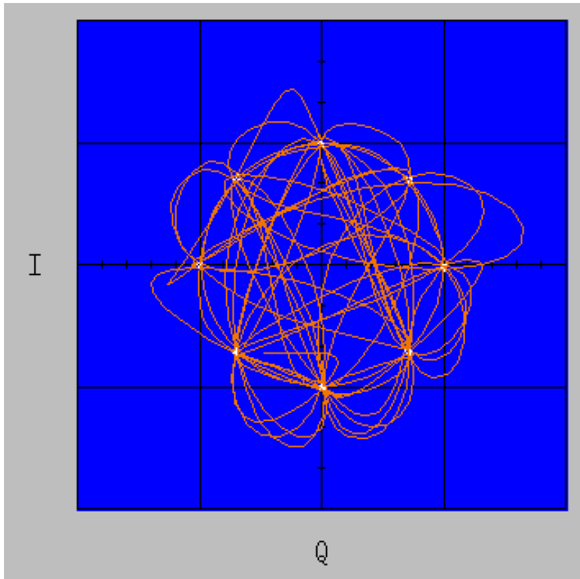
Information Bit Symbol	Symbol	CPQSK Phase Change	C4FM Deviation
01	+3	+135	+1.80 kHz
00	+1	+45	+0.60 kHz
10	-1	-45	-0.60 kHz
11	-3	-135	-1.80 kHz



Digital Modulator Type: C4FM

Rx Unmute Rule: No

CQPSK I-Q Map



How is 6.25 kHz Achieved for P25 Phase 2 ?

Two schemes considered

FDMA – possible but not chosen

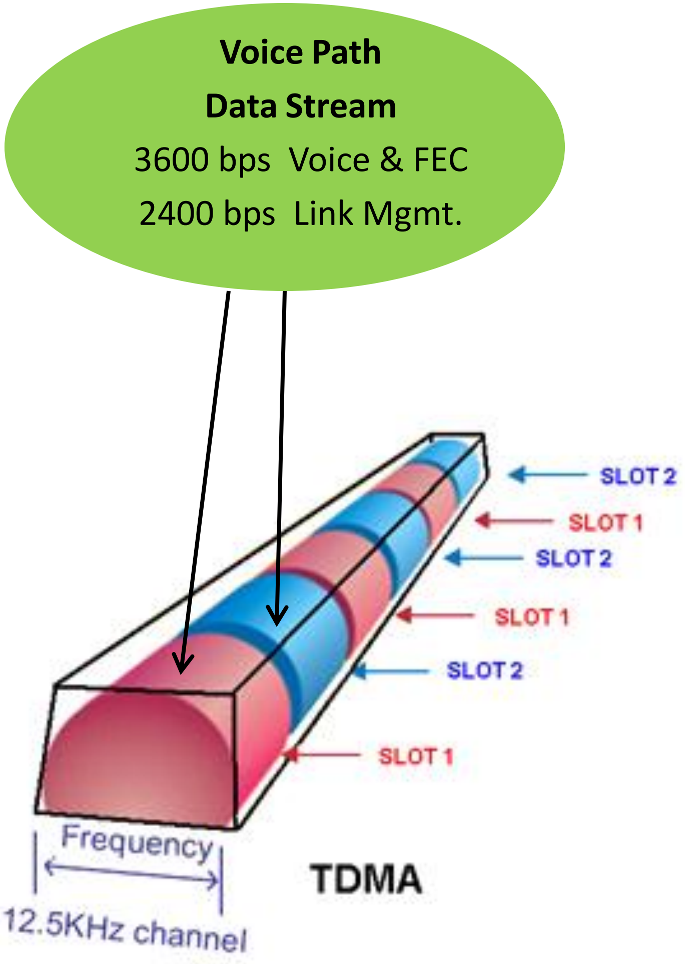
TDMA – chosen

History

- Legacy technology, well fielded
- GSM, IS-54/136 (D-AMPS) 30 kHz/3 slots
- TETRA 25 kHz/4 slots
- iDEN (Nextel) 25 kHz/3 slots
- P25 Phase 2   12.5 kHz/2 slots

PHASE 2

12 kbs Air Link Rate



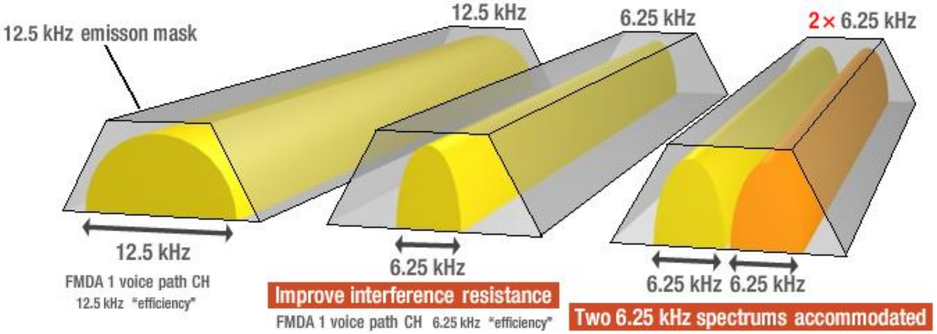
Voice Path

Data Stream

3600 bps Voice & FEC

2400 bps Link Mgmt.

FDMA



Phase 2 Equipment

Availability

- 2-slot TDMA base stations, mobiles and portables now available
- Dual-band and Tri-band capability (at a price !)
- Improved form factor and audio processing on TX and RX
- Dual Rate Vocoders **–** *full-rate* (7.2 kbs) and *half-rate* (3.6 kbs)
- Some models can be purchased Phase 1 and flash upgraded to Phase 2 later
- Linear Class A/AB amplifier design, increased size, power and cooling
- More expensive

Other Digital Radio Technology

Multiple VOCODER and Channel Access Technologies

Domestic and International Markets

- TETRA (ETSI European Open Standard)
- DMR Tier 2 & 3 (TDMA, 2-slot @ 12.5 kHz), MotoTRBO
- NXDN (FDMA 6.25 kHz)

DMR
DIGITAL MOBILE RADIO ASSOCIATION

TETRA

NEXEDGE™

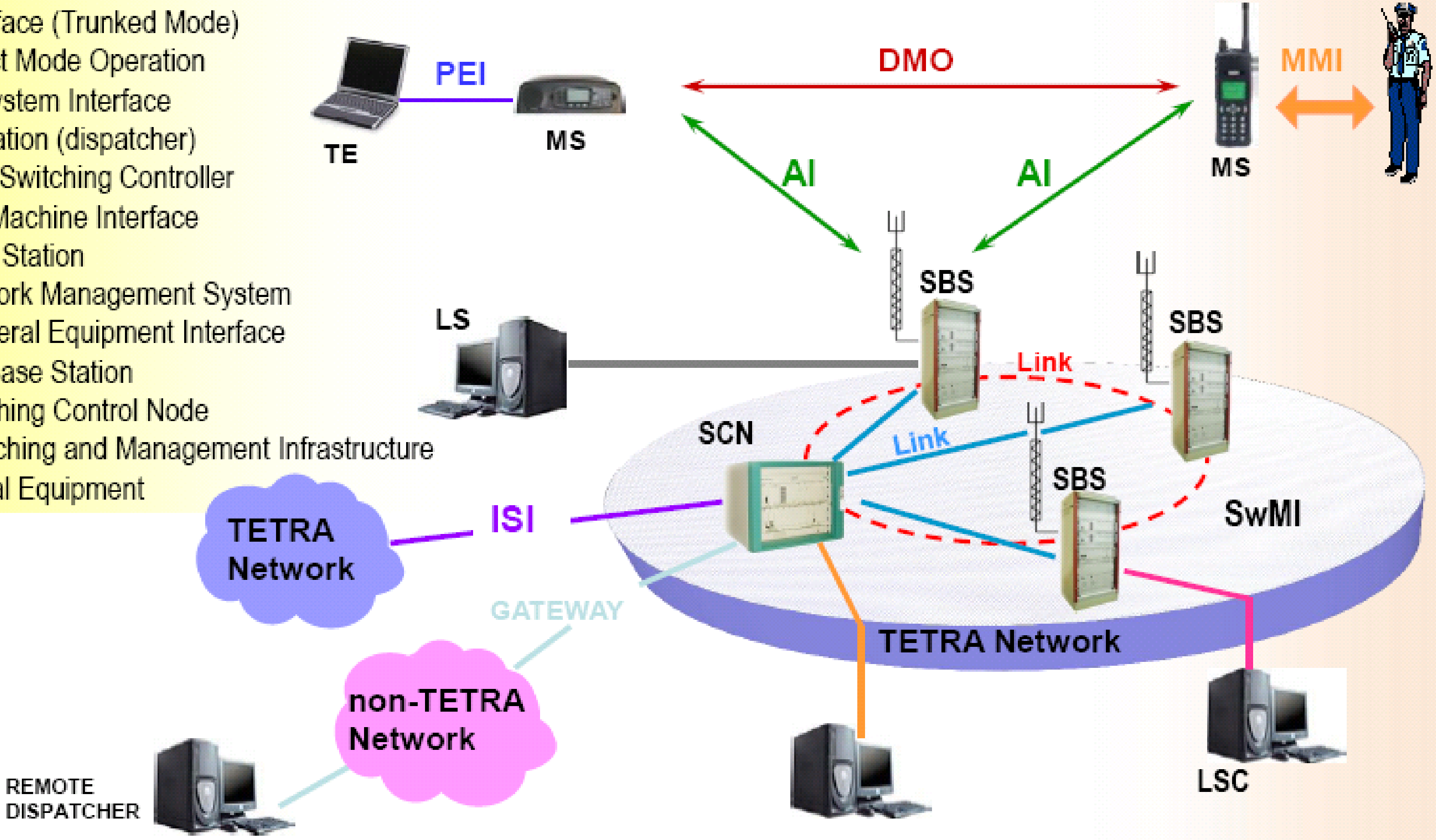
IDAS

TETRA

- TErestial Trunked Radio
- ETSI Standard EN300392, similar to GSM
- Suite of *open* digital trunked radio standards
- Targeting Public Safety and Professional Radio Market
- Key markets are governments and utilities
- Wide area (national) Private and Public Systems/Carriers
- Preceded P25 as a standard by about 5 years

TETRA Standard Elements and Interfaces

AI - Air Interface (Trunked Mode)
DMO - Direct Mode Operation
ISI - Inter-System Interface
LS - Line Station (dispatcher)
LSC - Local Switching Controller
MMI - Man Machine Interface
MS - Mobile Station
NMS - Network Management System
PEI - Peripheral Equipment Interface
SBS - Site Base Station
SCN - Switching Control Node
SwMI - Switching and Management Infrastructure
TE - Terminal Equipment



TETRA

- Supports trunked, conventional (repeater and simplex)
- Cellular-style site hand-off
- Relatively small base station coverage areas – approximately 33% - 50 % that of a analog system
- Supports High Capacity Call Loads
- Often implemented in cellular-style networks (low sites, low power, in-building cells)
- Significant bandwidth for site connectivity (2Mb/s typical)

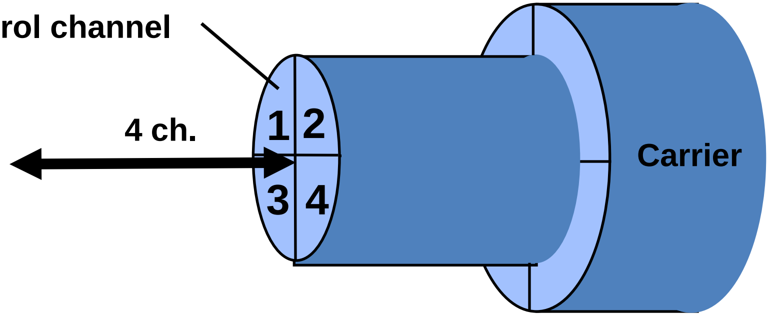
TETRA

National UHF TETRA Network AIRWAVE UK

- Private Public Partnership
- Serves public safety across 99% of UK
- 2300 networked base station sites
- 100,000 radio users, 41 dispatch centers
- 54 Police Agencies
- Motorola Dimetra IP TETRA trunked system

TETRA

- 4 slot TDMA in 25 kHz channels *(6.25 kHz 'equivalent')*
- π/4 DQPSK Modulation, ACELP vocoder @ 4.6 kbps
- Modulation has AM component – req. linear amp
- Gross Data Rate 36 kbps, multiple channels can be aggregated
- Circuit and packet mode data, Simultaneous Voice and Data
- 35 mile site range limit -propagation delays causing overlap of TDMA slots
- Data calls can use up to 4 ch. (multi-slot data)

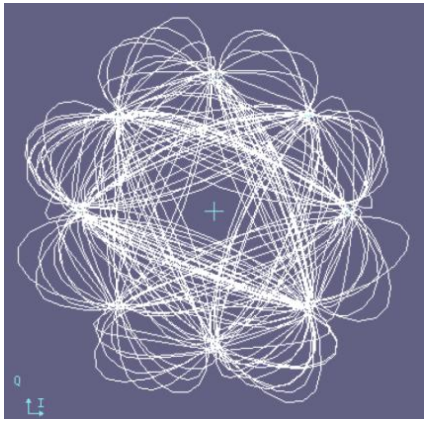


Note - 1 time slot dedicated for control channel

36 kbps gross bit rate

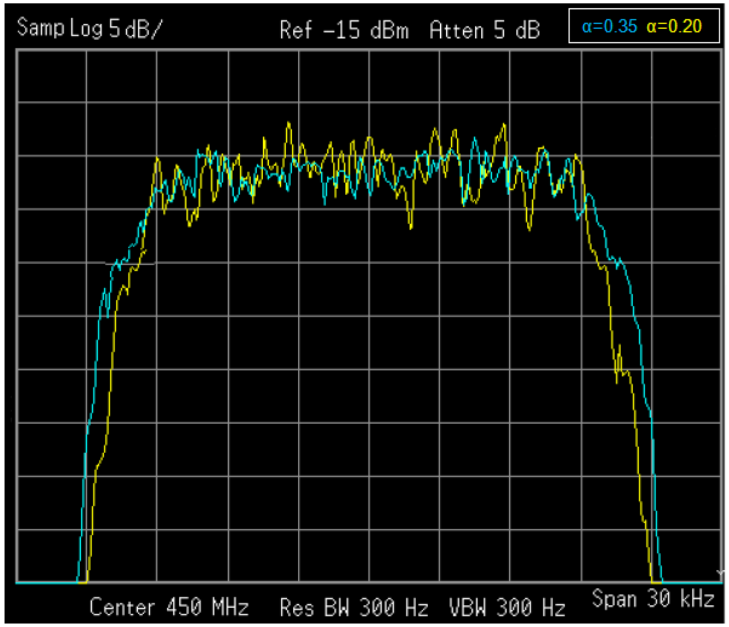
TETRA Trajectory plot displaying phase and amplitude carrier transitions, power deviations and targeting to symbol points.

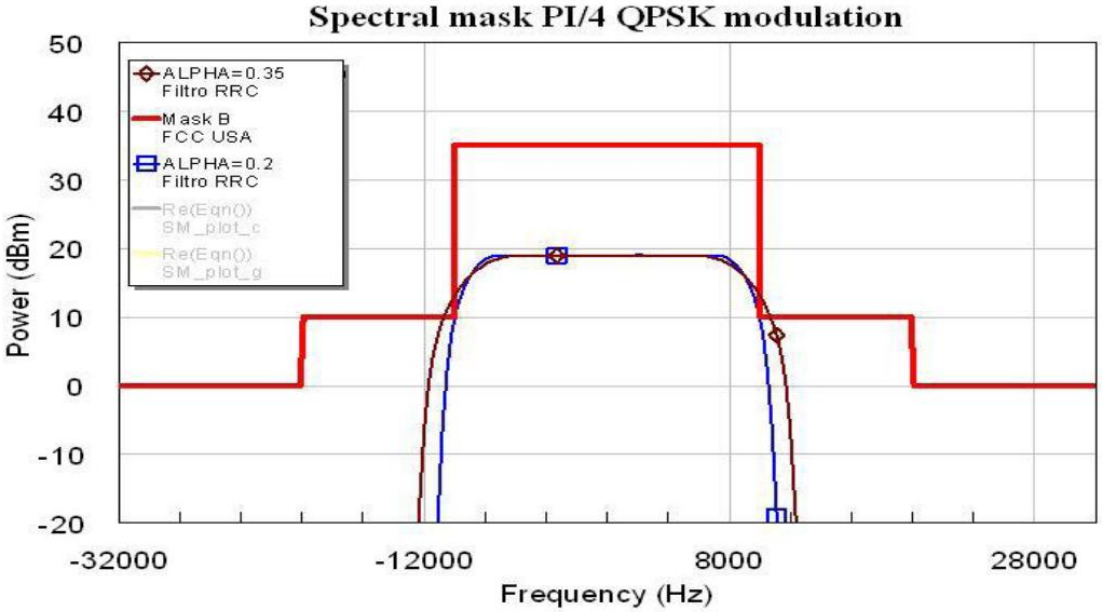
Look familiar….?



TETRA in the USA?

- Initially **not** OK – did not conform to FCC 47 CFR 2.1049 and Part 90.209
- Mask B and Occupied BW < 20 KHz (power radiated above and below the frequency limits must be ≤ 0.5 % of total mean emission power)
- Three options to meet this involved modifying:
  1. Modulation type: π/4-DQPSK1 2. Symbol rate: 18 Ksymbol/s 3. Modulation filter
- Industry responded by changing roll-off factor (α) of RRC filter: 0.35 > 0.20
- Now FCC acceptance granted





NXDN

- *"Open Proprietary"* Protocol co-developed by Kenwood and ICOM
- 6.25 kHz FDMA, C4FM (4-level FSK), 4.8 kbps channel rate
- AMBE +2™ vocoder @ 3.6 kbps (2,450 voice + 1,150 FEC)
- Mixed mode (6.25 kHz digital or 12.5 kHz analog)
- Conventional or trunked operation
- Single or multi-site networking via simple IP backhaul/linking
- Integrated Data Services – GPS data, status and text messaging

4K00F1W	NXDN Voice & Data 6.25 kHz
6K00F7W	D-Star, 6 kHz

"Skinny P25"

P25 and NXDN Modulation Comparison			
Information	**Symbol**	**C4FM Deviation(P25)**	**C4FM Deviation(NXDN)**
01	+3	+1800 Hz	+1050 Hz
00	+1	+600 Hz	+350 Hz
10	-1	-600 Hz	-350 Hz
11	-3	-1800 Hz	-1050 Hz
Channel BW		12.5 kHz	6.25 kHz

VOCODER Comparison		
Feature	**P25**	**NXDN**
Type	IMBE	AMBE +2
Speech Coding	4400 bps	2450 bps
FEC	2800 bps	1150 bps
Total Ch. Rate	7200 bps	3600 bps
RF Ch. Rate	9600 bps	4800 bps

NXDN

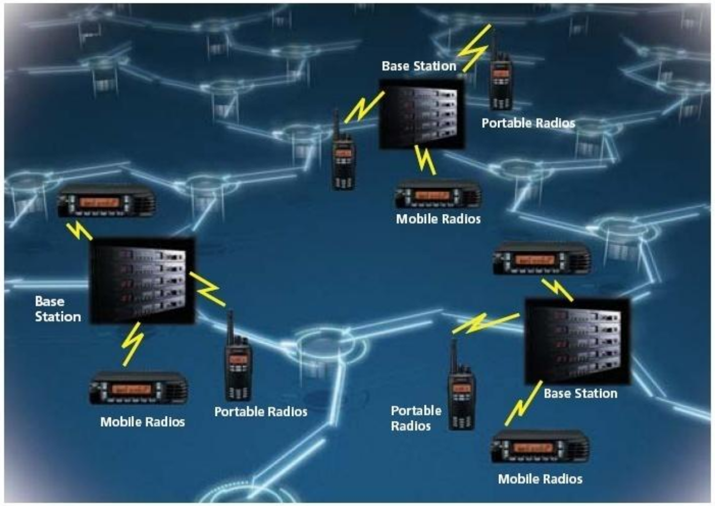
- Targeted for professional and utility markets
- Two manufacturers ICOM –IDAS™ and Kenwood – Nexedge™
- AAR recommended bypassing 25 kHz to 12.5 kHz directly to 6.25 kHz and NXDN compliance for Very Narrowband (VNB) operation.
- "Clean-cab" NXDN radio variants for railroad use

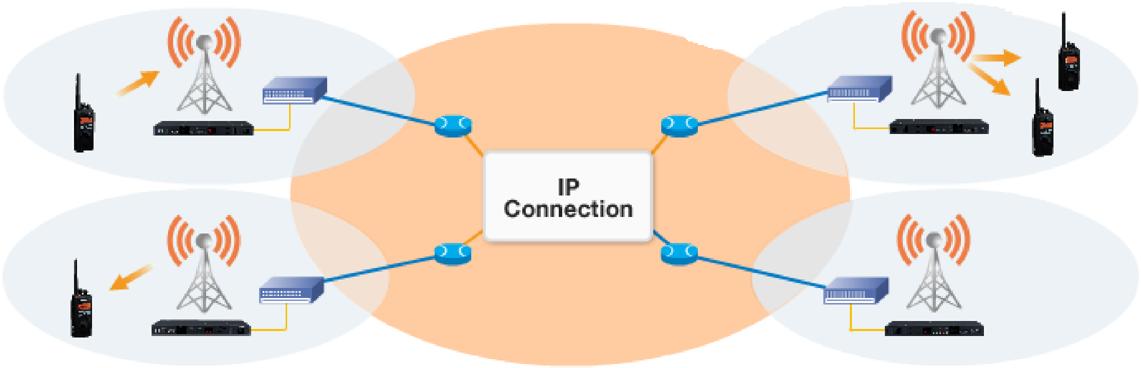
ASSOCIATION OF AMERICAN RAILROADS

NXDN

Wide Area Repeater Linking and Multi-site Networking

- Simple IP linking between sites with off-the-shelf components
- Modest IP bandwidth requirements (17 kbps/voice path, 128 kbps aggregate)
- Can utilize the internet as linking medium w/VPN
- Supports receiver voting and simulcast transmit

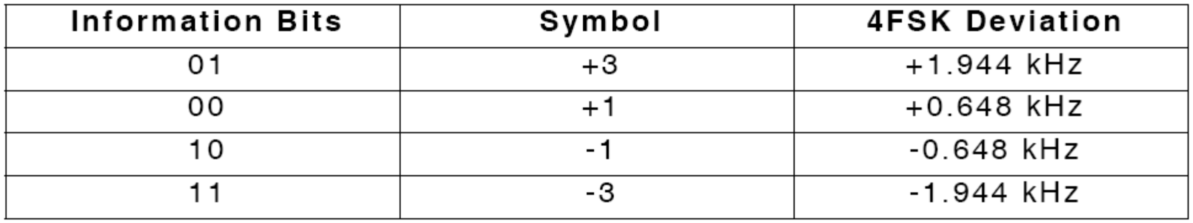




DMR

- Digital radio standard developed by ESTI in 2005
- TDMA 2-slot @ 12.5 kHz (6.25 kHz equivalent)
- 4-level FSK modulation, state-of-the-art Forward Error Correction
- Does *not* specify the vocoder and related signaling!
- ETSI standard supports 3 "Tiers" of operation:
  - Tier I - license-free (FRS equivalent), 6.25 kHz FDMA
  - Tier II - licensed conventional, Tier III - licensed trunked
- Tier III supports Integrated Voice & Data / messaging
  - 128 character status msg, Short messaging (max. 288 bits of data)
- Supports packet data service (IPv4 and IPv6)

7K60FXE 2-slot TDMA DMR Voice



Information Bits	Symbol	4FSK Deviation
01	+3	+1.944 kHz
00	+1	+0.648 kHz
10	-1	-0.648 kHz
11	-3	-1.944 kHz

DIBIT Symbol Mapping to 4FSK Deviation

DMR

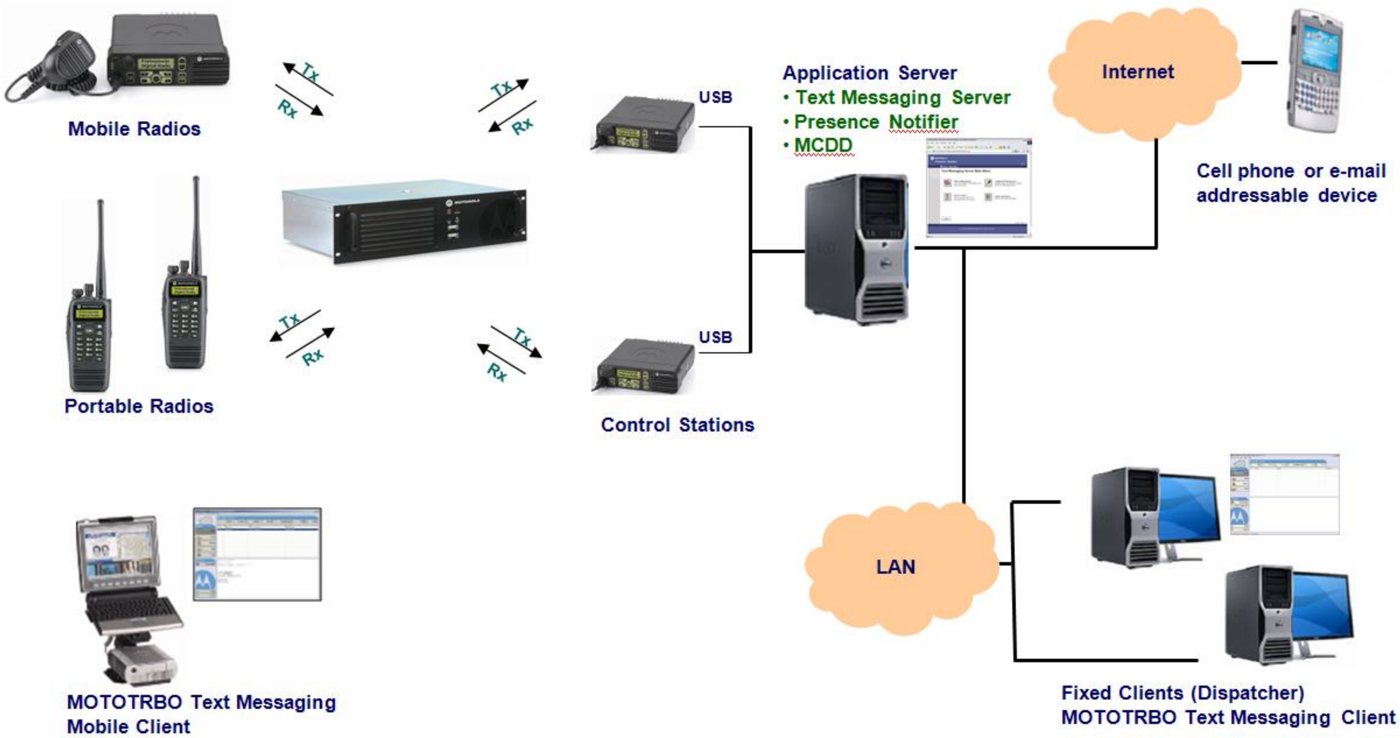
- Mixed analog/digital mode with automatic switching
- IP backhaul for simple site linking
- Supports simulcast operation and automatic roaming
- Available from Motorola (MotoTRBO ™) and Hytera
- Vertex Standard and Tait announced future commitment to DMR
- Direct mode falls back to 12.5 kHz efficiency as synchronization for 2-slot operation that repeater provides is not available.

Targeted for Professional and Utility Markets

DMR

MotoTRBO Features

- GPS data support and Text messaging
- TDMA claims longer battery life (50% duty cycle)
- IP Site Linking through base station Ethernet port and routers
- Application developers licensing program



Conclusions

What do I take away from this…?

- Similar issues facing amateur radio have been addressed by the public safety and professional radio industry over a decade ago
- Digital modulation technology offers operational and performance benefits to users that analog can no longer provide
- A transition to open standards and protocol development is now a reality
- User requirements, specifications, technology choices and capabilities are now being formed by closely coordinated working groups, technical committees representing the interests of end users, *not radio manufacturers*
- Both TDMA and FDMA offer the ability to achieve 6.25 kHz or equivalent channel BW for unprecedented spectral efficiency
- A single VOCODER manufacturer virtually dominates the LMR industry
- Low cost, low bandwidth, IP based site linking is common across multiple technologies for building wide area linked repeaters

Food for Thought

As a radios service, and very large 'user group', where do we stand..?

- Although required narrow-banding above 50 MHz has not, and perhaps will never be mandated by the FCC, what would we do if we had to…? What if H.R. 607 or similar future bill became law…?
- As a community, have we formally endeavored through committee or recognized body to define what our future communications capabilities and needs really are to support emergency communications, spectrum conservation, and basically to do more with less via technology? And put that into a document creating a standard.
- Would or should the industry listen and respond…?

THANK YOU !

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